The Interacting Dwarf Galaxy NGC 3077: The Interplay of Atomic and Molecular Gas with Violent Star Formation

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ABSTRACT

We present a comprehensive multi–wavelength study of the nearby interacting dwarf galaxy NGC 3077 (member of the M 81 triplet). High resolution VLA H I observations show that most of the atomic gas (∼90%) around NGC 3077 is situated in a prominent tidal arm with a complex velocity structure. Little H I ($\sim 5 \times 10^7 M_\odot$) is associated with NGC 3077 itself. High resolution OVRO observations of the molecular component (CO) reveal the presence of 16 molecular complexes near the center of NGC 3077 (total mass: $\sim 1.6 \times 10^6 M_\odot$). A virial mass analysis of the individual complexes yields a lower CO–to–H_2 conversion factor in NGC 3077 than the Galactic value - a surprising result for a dwarf galaxy. The lower conversion factor can be explained by extreme excitation conditions and the metallicity of the molecular gas. The total (atomic and molecular) gas content in the centre of NGC 3077 is displaced from the stellar component of NGC 3077 – this implies that not only the gas at large galactocentric radii is affected by the interaction within the triplet but also the center. We speculate that the starburst activity of NGC 3077 was triggered by this redistribution of gas in the center: Hα as well as Paα images show the presence of violent central star formation as well as dramatic ionized supershells reaching galactocentric distances of ∼1 kpc. Some of these supershells are surrounded by neutral hydrogen. In a few cases, the rims of the ionized supershells are associated with dust absorption. The most prominent star forming region in NGC 3077 as probed by Paα observations is hidden behind a dust cloud which is traced by the molecular complexes. Correcting for extinction we derive a star forming rate of 0.05 $M_\odot\,\mathrm{year}^{-1}$, i.e. given the reservoir in atomic and molecular gas in NGC 3077, star formation may proceed at a similar rate for a few 10^8 years. The efficiency to form stars out of molecular

gas in NGC 3077 is similar to that in M 82.

Subject headings: galaxies: individual (NGC 3077) – galaxies: dwarf – galaxies: ISM – galaxies: interactions – galaxies: kinematics and dynamics – ISM: molecules – ISM: HI

1. Introduction

NGC 3077 is a prominent example of an interacting dwarf galaxy. Together with the prototypical starburst galaxy M 82 and the spiral galaxy M 81 it forms the famous M 81 triplet. Although an interaction between the three galaxies is not at all obvious at optical wavelengths (but see Arp 1965, Getov & Georgiev 1988) it has been long known through observations in the H I line that the 3 galaxies are interacting: H I tidal arms and tails connect the three galaxies over a projected distance of more than 70 kpc (Cottrell 1977, van der Hulst 1979, Yun *et al.* 1994). The outstanding star forming activity in M 82 is usually attributed to the gravitational interaction with M 81 and/or NGC 3077.

Although the molecular and starburst properties of M 82 have been the subject of innumerable studies, little is known about its starforming neighbor, NGC 3077. This is surprising since it has been long known that NGC 3077 is experiencing intense star formation (e.g., Barbieri *et al.* 1974). As noted by Price & Gullixson (1989) it is difficult to classify NGC 3077 on basis of its optical morphology. Emission line studies of NGC 3077 (e.g., Price & Gullixson 1989; Thronson, Wilton & Ksir 1991 (TWK91); Martin 1997, 1998, 1999) show that streamers and supershells of ionized gas surround a bright core of Hα emission. This core is also associated with soft X–ray emission, consistent with intense star formation in the center (Bi et al. 1994). Molecular gas in the center was detected by Becker et al. (1989) using the IRAM 30 m telescope. First interferometric maps of the molecular component of NGC 3077 using the OVRO millimeter array have been presented by Thronson & Carlstrom (1992) and Meier, Turner & Beck (2001). Some general information about NGC 3077 is compiled in Tab. 1.

The H I in NGC 3077 is strongly disrupted by the interaction with its two neighbors M 81 and M 82: most of the neutral gas is located in a prominent tidal arm east of NGC 3077 (e.g., van de Hulst 1979, Yun 1994, Walter 1999). Walter & Heithausen (1999, see also

Heithausen & Walter 2000) recently discovered a massive molecular complex in this tidal feature. Numerical simulations suggest that the gas in the tidal arm has been stripped off the outskirts of NGC 3077 during the latest close encounter with M81, some 3 $\times 10^8$ yr ago (Brouillet *et al.* 1990, Thomasson & Donner 1993, Yun et al. 1993). This is in contrast to the suggestion of some authors (Price & Gullixson 1989, Bi et al. 1994, TWK91), that NGC 3077 accreted ('stole') H I from M 81 in this recent interaction. In the following, we will assume a distance to NGC 3077 of 3.2 Mpc (Tammann & Sandage 1968). We note that this value has recently refined to be 3.9 Mpc (Sakai & Madore 2001), i.e., 20% higher, however we decided to use the old distance to make it easier to compare our results to earlier studies.

In this paper, we attempt to shed more light on the atomic and molecular gas as well as the starburst properties of NGC 3077 and present a multi–wavelength study of this fascinating galaxy. In Section 2 we describe the observations of the atomic gas (H I, VLA), molecular gas (CO, OVRO), optical broad and narrow band (KPNO) and the NIR (NICMOS HST). The different wavelengths are then compared and discussed in detail in Section 3. Section 4 summarizes the most important results of our study and relates the gas and star formation properties of NGC 3077 to those of its neighbor, M 82.

2. Observations and Data presentation

2.1. CO–observations

We observed NGC 3077 in the CO(1→0) transition using the Owen's Valley Radio Observatory's mm array (OVRO) in C, L and H configurations. In total, 44 hours were spent on source; the observational details are listed in Table 2. Data were recorded using two simultaneous correlator setups resulting in velocity resolutions of 5 and 1.3 km s^{-1} (after

Table 1: General information on NGC 3077

Object	NGC 3077 (UGC 5398)
Right ascension (J2000.0)[a]	$10^{h}03^{m}19\overset{s}{.}23$
Declination (J2000.0)[a]	$68^\circ\ 43'\ 59''$
Adopted distance[b]	3.2 Mpc
Scale	15.5 pc/$''$
Systemic velocity[c]	5 $\mathrm{km\,s^{-1}}$
Apparent magnitude (B)[d]	10.6 mag
Distance modulus	m_B-M_B=27.6
Corrected absolute magnitude (B)[d]	-17.0 mag
Blue luminosity L_B	$9.3\times10^{8}\ L_{B\odot}$
H I mass M_{HI}[c]	$3-10\times10^{7}\ M_\odot$
H I mass to blue light ratio M_{HI}/L_B	0.03–0.1 $M_\odot/L_{B\odot}$
Hα luminosity[e]	$4.6\times10^{39}\ \mathrm{erg\,s^{-1}}$
Paα luminosity[e]	$9.5\times10^{38}\ \mathrm{erg\,s^{-1}}$
star formation rate[e]	0.05 $M_\odot\ \mathrm{yr^{-1}}$
H_2 mass[f]	$8\times10^{5}\ M_\odot$

[a] RC 3, de Vaucouleurs et al. 1991

[b] see text

[c] depending on the aperture, see Sec. 3.1

[d] magnitudes are only corrected for extinction within the Milky Way, see TWK91

[e] this study, see Sec. 3.4, note that the Hα flux published by Price & Gullixson (1989) is off by a factor of 20 (TWK91)

[f] this study, see Sec. 3.2.2

Hanning smoothing) with a total bandwidth of 320 and 80 $\mathrm{km\,s^{-1}}$, respectively. Unless otherwise mentioned, the results presented in this paper were derived using the 1.3 $\mathrm{km\,s^{-1}}$ resolution data. Flux calibration was determined by observing 1328+307 (3C286) and Neptune for approximately 20 minutes during each observing run. These calibrators and an additional noise source were used to derive the complex bandpass corrections. The nearby calibrators 1031+567 (1.1 Jy) was used as secondary amplitude and phase calibrator. The data for each array were edited and calibrated separately with the MMA and the AIPS packages. The *uv*–data were inspected and bad data points due to either poor atmospheric coherences or shadowing were removed, after which the data were calibrated.

Two sets of datacubes were produced using the task IMAGR in AIPS, each of them CLEANed to a level of two times the rms noise (Högbom 1974, Clark 1980). The first data set was made with natural weighting, leading to a resolution of $3.7'' \times 3.0''$ (57×46 pc) and emphasizing large scale structures (noise: 16 mJy beam^{-1}; 0.13 K in a 5 $\mathrm{km\,s^{-1}}$wide channel, 35 mJy beam^{-1}; 0.29 K in a 1.3 $\mathrm{km\,s^{-1}}$ channel). A second cube was produced using the ROBUST weighting scheme (Briggs 1995). Eventually, we chose a value of ROBUST=0.25, resulting in a beamsize of $2.4'' \times 1.9''$ (37×29 pc) and an rms noise of 22 mJy beam^{-1} (0.44 K, 5 $\mathrm{km\,s^{-1}}$wide channels). This latter resolution starts to resolve individual giant molecular clouds (GMCs) in NGC 3077.

To separate real emission from noise when deriving moment maps we applied the following procedure: the natural weighted data cube was convolved to a circular beam with a FWHM of $10''$. The smoothed map was then tested at the 2σ level; if a pixel fell below this level, the counterpart in the cube was blanked. After that, the remaining peaks were inspected. Emission that was present in 3 consecutive channels was considered to be real while all other remaining spikes were considered to be noise and blanked. The final result was named the MASTER cube. This mask was used to blank the original NATURAL

and ROBUST data cubes. This method ensures that the same regions are included when inspecting cubes at different resolutions and with different signal–to–noise ratios. To derive physical properties, the CO data were primary beam corrected.

2.2. HI–observations

NGC 3077 was observed with the NRAO[2] Very Large Array (VLA) in B–, C– and D–configuration. Part of the D–array observations were affected by solar interference, which was removed by deleting *uv*–spacings shorter than typically 0.4 kλ. In total, 17 hours were spent on source which were divided into 4 hours for D–array, 2.5 hours in C–array and 10.5 hours in B–array (see Table 3 for a detailed description of the VLA observations). The flux calibration was determined by observing 1328+307 (3C286) for approximately 20 minutes during each observing run, assuming a flux density of 14.73 Jy according to the Baars *et al.* (1977) scale. This calibrator was also used to derive the complex bandpass corrections. The nearby calibrators 1031+567 and 0945+664 were used as secondary amplitude and phase calibrators and their fluxes were determined to be 1.80 Jy and 2.22 Jy, respectivey. Since the systemic velocity of NGC 3077 (~ 5 $\mathrm{km\,s^{-1}}$) overlaps in velocity with Galactic H I emission, each calibrator observation was observed at velocities shifted by +300 $\mathrm{km\,s^{-1}}$ and –300 $\mathrm{km\,s^{-1}}$ to avoid Galactic contamination. In the course of the calibration these observations were then averaged to give interpolated amplitude and phase corrections. NGC 3077 was observed using a 1.56 MHz bandwidth centered at a heliocentric velocity of 38 $\mathrm{km\,s^{-1}}$. This band was divided into 128 channels resulting in a velocity resolution of 2.58 $\mathrm{km\,s^{-1}}$ after online Hanning smoothing. In editing and analysing the data we followed the

[2]The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

Table 2: OVRO–setup during the observations

OVRO configuration	C	L	H
baselines	$7-22\,\mathrm{k}\lambda$	$6-44\,\mathrm{k}\lambda$	$13-92\,\mathrm{k}\lambda$
	$(20-60\,\mathrm{m})$	$(15-115\,\mathrm{m})$	$(35-241\,\mathrm{m})$
date of observation	1999 Sep. 22	1999 Nov. 10	1999 Dec. 16
	1999 Sep. 24	1999 Nov. 13	1999 Dec. 17
total time on source	800 min	900 min	950 min
total bandwidths		124 MHz, 31 MHz	
No. of channels		62, 62	
velocity resolution		5 $\mathrm{km\,s^{-1}}$, 1.3 $\mathrm{km\,s^{-1}}$	
central velocity		7 $\mathrm{km\,s^{-1}}$	
angular resolution[a]		2.4×1.9 arcsec	
linear resolution[a]		37×29 pc	
rms noise[a,b]		22 $\mathrm{mJy\,beam^{-1}}$ (0.44 K)	

[a]based on ROBUST data cube; see text

[b]5 $\mathrm{km\,s^{-1}}$ channel

same procedure as outlined in the previous section (including the production of a MASTER cube). Obtaining fluxes for extended emission in multi-array observations is non–trivial – here we followed the procedure described in Walter & Brinks (1999).

We also calculated a radio continuum image of NGC 3077 at 21 cm by using the line–free channels of the VLA H I observations; here we boosted the resolution to $5''$ (~ 77.5 pc) by employing uniform weighting (rms: 0.4 mJy beam^{-1}).

2.3. Optical and NIR Observations

Narrowband images were obtained January 2-10, 2000 at the Kitt Peak National Observatory 2.1m telescope at λ6487 (67ÅFWHM) and 6571$\AA$ (FWHM 84Å). The CCD frames were corrected for zero level bias offsets, pixel-to-pixel bias variations, and pixel-to-pixel sensitivity fluctuations. After constructing cosmic ray masks for each frame, and registering the frames, the images in each bandpass were co-added to obtain on-band and off-band images. These images were flux calibrated using observations of spectrophotometric standards (Massey *et al.* 1988). The off-band continuum was scaled iteratively to match the stellar continuum in the on-band image and then subtracted from it. The net emission-line image contains both [NII] $\lambda\lambda 6548, 6583$ and Hα emission. The spectroscopic observations discussed here are described in Martin (1998).

We retreived NICMOS broad and narrow band images from the HST archive (PI: Sparks, H: dataset N4K40JP3Q, Pα: N4K40JP2Q, both images were obtained on June 16, 1998). In calibrating the images, we followed the approach given in Böker et al. (1999). The continuum was subtracted from the Paα images and the flux in the Paα line was derived using:

$$F_{\rm line} = 1.054 \times FWHM \times PHOTFLAM \times CR$$

Table 3: Setup of the VLA during the observations

VLA configuration	B	C	D
baselines	$1 - 54\,\mathrm{k}\lambda$	$0.34 - 16\,\mathrm{k}\lambda$	$0.166 - 4.9\,\mathrm{k}\lambda$
	$(0.21 - 11.4\,\mathrm{km})$	$(0.073 - 3.4\,\mathrm{km})$	$(0.035 - 1.03\,\mathrm{km})$
date of observation	1992 Jan. 18	1992 Apr. 20	1991 Mar. 03
	1992 Jan. 19		1992 Sep. 03
total time on source	647 min	133 min	245 min
total bandwidth		1.56 MHz	
No. of channels		128	
velocity resolution		$2.58\ \mathrm{km\,s^{-1}}$	
central velocity		$14\ \mathrm{km\,s^{-1}}$	
angular resolution[a]		13.0×12.7 arcsec	
linear resolution[a]		200×200 pc	
rms noise[a,b]		$1.0\ \mathrm{mJy\,beam^{-1}}$ (3.7 K)	

[a]based on NATURAL data cube

[b]$2.58\ \mathrm{km\,s^{-1}}$channel

where $FWHM = 191\mathring{A}$, $PHOTFLAM = 4.685 \times 10^{-18}\,\mathrm{erg\,cm^{-2}\,\mathring{A}^{-1}\,DN}$ (the latest value given in the NICMOS handbook) and CR is the countrate ($\mathrm{DN\,s^{-1}}$). We have also obtained near infrared broad–band J, H and K images from the 2MASS project.

3. Results

3.1. The distribution of Neutral Hydrogen

The distribution of neutral hydrogen at high angular resolution (moment 0 map, corrected for primary beam attenuation) is presented in Fig 1, right. Most of the H I in the region is situated in the prominent eastern tidal arm, little H I is associated with the optical counterpart of NGC 3077 (contours).

To obtain accurate H I masses for NGC 3077 we defined 3 different apertures as indicated in Fig. 1. The largest aperture (I) accounts for most of the H I in the field of view. Aperture II only includes H I which is roughly associated with the optical body of NGC 3077 — the smallest aperture (III) only accounts for the central nucleus. The total fluxes (and masses, adopting a distance to NGC 3077 of 3.2 Mpc) for the apertures are: (I): 192.3 Jy $\mathrm{km\,s^{-1}}$ (4.8×10^8 $M_\odot$), (II): 42.13 Jy $\mathrm{km\,s^{-1}}$ (1.0×10^8 $M_\odot$) and (III): 11.30 $\mathrm{km\,s^{-1}}$ (2.8×10^7 $M_\odot$). The H I content associated with the optical body of NGC3077 is therefore somewhere between $3 - 10 \times 10^7$ $M_\odot$ (depending on the aperture chosen).

As mentioned in the Introduction, the massive H I complex east of NGC 3077 has presumably been stripped off the outskirts of NGC 3077 during the recent interaction with M 81. Evidence for this comes from numerical simulations (e.g., Yun et al. 1993) which show that the material in the tidal arm east of NGC 3077 originally belonged to NGC 3077 itself. This scenario is supported by the high–resolution H I observations: Figure 2 shows the H I velocity field of NGC 3077 and the region around it. The mean velocity of the tidal

feature is $v = 15$ km s^{-1} and close to the one of NGC 3077 ($v_{\rm sys} = 5$ km s^{-1}). Note that the systemic velocity of M 81 is some $v_{\rm sys} = 50$ km s^{-1} with velocities reaching $v = -250$ km s^{-1} in the spiral arms pointing towards NGC 3077 (Westpfahl & Adler 1996). We also find no evidence for H I mass accretion and/or infall onto the centre of NGC 3077 in our H I data. All this renders the possibility that the material originally belonged to M 81 unlikely. An additional (but somewhat weaker) argument comes from the fact that the H I mass to blue light ratio in centre of NGC 3077 is only ~ 0.05 $M_\odot/L_{B\odot}$ (see Tab. 1). If the H I in the tidal arm previously belonged to NGC 3077 the H I mass to blue light ratio is more like $\sim 0.5 M_\odot/L_{B\odot}$, more typical for dwarf irregular galaxies (this argument obviously only holds if NGC 3077 was not a dwarf elliptical before the interaction). We conclude that the tidal gas around NGC 3077 originated from NGC 3077 itself. We note that since the total mass of the tidal system is similar in mass to NGC 3077 itself (Heithausen & Walter, 2000), a complete detachment of this system (i.e., the creation of a true tidal dwarf system) is likely (but see Meier, Turner & Beck 2001).

The lines in Fig. 2 indicate the orientation of 3 position velocity (pv) diagrams through the H I distribution around NGC 3077 as shown in Fig 3. Multiple velocity components are visible where the H I emission in the tidal feature is strongest. The cuts along the tidal arms towards M 81 and M 82 show a rather smooth velocity gradient away from the the H I maximum in the tidal feature. The first pv diagram (Fig. 3, I) cuts through the center of NGC 3077 and the prominent tidal feature. The bright emission at offset 2.3′ is NGC 3077 itself. Multiple velocity components are visible in the tidal feature (around offset -2′). The second (II) and third (III) pv diagrams are oriented along the prominent tidal arms which roughly point towards M 82 (north, cut II) and M 81 (west, cut III). They show a rather smooth velocity gradient away from the H I maximum in the tidal feature.

3.2. The Distribution of Molecular Gas

3.2.1. Global properties

The CO(1–0) channel maps as obtained with OVRO are shown in Fig. 4 (based on the natural weighted data at 1.3 $\mathrm{km\,s^{-1}}$ resolution). Clearly, the CO emission in NGC 3077 originates from many different sub–structures. These sub–clumps are even better visible in position velocity diagrams as the one presented in Fig. 5 (at high spatial and velocity resolution – the orientation of this cut is indicated in Fig. 6, left). The numbers in this plot refer to the individual subclumps discussed in Sec. 3.2.2. The CO intensity distribution (moment 0) is presented in Fig. 6 (left: natural weighting, emphazising diffuse emission, right: robust weighting, focussing on the small scale structure). Globally, we detected 4 molecular regions which are labeled R1 – R4 in Fig. 6.

3.2.2. Clump decomposition and molecular cloud masses

R1 – R3 have a complex velocity structure and consist of multi–velocity components. To analyze the substructure of these molecular complexes we decomposed the robust weighted ($\sim 2''$, high velocity (1.3 $\mathrm{km\,s^{-1}}$) resolution data cube with a gaussian clump fitting code (Stutzki & Güsten 1990) as well as by eye. The clump fitting code (‘Gaussclump’) determines the maximum in the data cube and subtracts a 3D gaussian fit to the data (RA, DEC, velocity) from the cube. The procedure works iteratively on the residual until the specified RMS level (5 sigma in this case) is reached. In this procedure the spatial and velocity resolution is taken into account (for further detail see Stutzki & Güsten 1990). Each clump determined by ‘Gaussclump’ was checked by eye using pv-cuts and by inspecting spectra at individual positions. In case of doubt we reran Gaussclump with different parameters for contrast, minimum spatial and velocity structures and other parameters

controlling the gaussian fit. The parameters for our final clump decomposition of the data set are given in Tab. 4. Parameters regarding the spatial and velocity information as well as the flux (column 2 to 7) refer to the fit results. In total we identified 16 CO complexes within NGC 3077 (Tab. 4). To emphasize the complex substructure we show a pv-diagram (along the line shown in Fig. 6, left) in Fig. 5. Nine out of the 16 components are at least partly visible in this diagram and are labeled by their respective number. The size of most of the clumps is comparable to our beam implying that most of the CO emission is not resolved at a linear resolution of $\sim 30\,\mathrm{pc}$. The radius and the velocity width shown in Tab. 4 are deconvolved for the beam–size as well as the velocity–width. For measured values less than 1.1 times the resolution, the estimate is listed as an upper limit. The approximate errors for the measured quantities are given in the footnote of Tab. 4. We derived cloud masses assuming that the clouds are virialized using $M_{\rm vir} = 250 \times v_{\rm FWHM}[\,\mathrm{km\,s^{-1}}]^2 \times R[\mathrm{pc}]$ (Rohlfs & Wilson, 1996; see Tab. 4 column 8). We also derived molecular masses assuming a Galactic conversion factor ($X_{CO} = 2.3 \times 10^{20}\,\mathrm{cm^2\,K^{-1}\,km^{-1}\,s}$, Strong *et al.* 1988) using $M = 1.23 \times 10^4 \times (3.2)^2 \times S_{CO}\,M_\odot$ (column 9). Complexes 1 to 5 are the components associated with region R1, complexes 6 to 11 belong to R2, complexes 12 to 15 belong to R3 and complex 16 is the diffuse CO component in the north–west of NGC 3077 (R4). The virial masses for clouds in R1–R3 are significantly lower than the masses derived from converting CO luminosities to H_2 column densities (using the Galactic conversion factor). In column 10 we present the derived conversion factor $X_{\rm CO}$ based on the assumption that the complexes are indeed virialized. On average, we get values below $1.0 \times 10^{20}\,\mathrm{cm^{-2}\,(K\,km\,s^{-1})^{-1}}$ (see the discussion in Sec. 4). We note that Meier, Turner & Beck (2001) derived a Galactic conversion factor for NGC 3077 (see their paper for details).

In the following we will adopt a conversion factor of $1 \times 10^{20}\mathrm{cm^{-2}(K\,km\,s^{-1})^{-1}}$ for NGC 3077 (roughly half of the Galactic value), primarily for convenience. Using this conversion factor, the total H_2 mass of NGC 3077 is $1.6 \times 10^6\,\mathrm{M_\odot}$ (this is counting the

complexes discussed above as well as diffuse emission that has not been catalogued). Becker et al. (1989) observed the center of NGC 3077 with the IRAM 30 m telescope in the CO($1 \rightarrow 0$) and CO($2 \rightarrow 1$) transition at resolutions of $21''$ and $13''$, respectively. They only present the CO($2 \rightarrow 1$) data in their paper and conclude that a giant molecular complex with a velocity width of 30 $\mathrm{km\,s^{-1}}$ and a diameter of 320 pc (FWHM) is located near the center. Using a conversion factor of $4 \times 10^{20}\,\mathrm{cm^{-2}(K\,km\,s^{-1})^{-1}}$ they derive a total molecular mass of $1 \times 10^{7}\,\mathrm{M_{\odot}}$ and a virial mass of $3 \times 10^{7}\,\mathrm{M_{\odot}}$. Obviously, our higher resolution observations show that their complex breaks up into many smaller complexes. The linewidth used by Becker *et al.* to derive the virial mass therefore measured the velocity dispersion of the CO clumps rather than the intrinsic linewidth of a gravitational bound complex – their virial mass is therefore too high. Nevertheless our mass estimate based on the measured CO intensity of $1.6 \times 10^{6}\,\mathrm{M_{\odot}}$ is about a factor of 1.5 less than the H_2 mass derived by Becker *et al.* (taking the different conversion factors into accout). This indicates that we may miss some extended emission in our interferometer data.

3.3. Comparison between the atomic and molecular gas phase

The CO and H I distribution are compared in Fig. 7 (left). The greyscale and the thin countours represent the H I surface brightness. The thick contours represent the CO distribution as shown in Fig. 4 (right). Note the apparent asymmetry between the H I and the CO distribtion: the H I maxima is located east of the CO maximum. Most of the CO emission is located in an H I depression – this suggests that atomic material in this region has largely turned molecular. The total H I mass in the area shown is $\sim 8 \times 10^{6}\,\mathrm{M_{\odot}}$.

We created a total gas column density map by combining the H I and CO moment maps (Fig. 10, right). The CO data were first convolved to the resolution of the H I map

Table 4: Properties of the CO clumps in NGC 3077

	RA (2000)	DEC (2000)	v_{lsr}	$dv^a_{\rm FWHM}$	r^a	S_ν	M_{vir}	$M^b_{H_2}$	$X^c_{\rm co}$
			$[\rm km\,s^{-1}]$	$[\rm km\,s^{-1}]$	[pc]	$[\rm Jy\ km\,s^{-1}]$	$[10^4\ M_\odot]$	$[10^4\ M_\odot]$	$[10^{20}\,\rm cm^2\,K^{-1}\,km^{-1}\,s]$
1	10:03:18.95	68:43:57.37	24.5	4.5	< 17	1.15	< 8.4	14.5	< 1.3
2	10:03:18.67	68:43:55.38	21.9	1.2	< 17	0.42	< 0.6	5.2	< 0.3
3	10:03:19.32	68:44:00.36	19.2	2.1	< 17	0.62	< 1.8	7.8	< 0.5
4	10:03:18.86	68:43:56.88	15.5	6.2	24	3.36	22.1	42.4	1.2
5	10:03:19.14	68:44:00.37	11.6	3.4	< 17	1.07	< 4.7	13.5	< 0.8
6	10:03:18.77	68:43:56.38	6.4	3.1	< 17	0.92	< 4.0	11.6	< 0.8
7	10:03:18.95	68:44:01.37	-2.8	1.9	18	0.62	1.5	7.8	0.4
8	10:03:18.78	68:44:00.38	-8.0	2.5	< 17	0.56	< 2.5	7.0	< 0.8
9	10:03:18.86	68:43:59.88	-13.0	1.6	< 17	0.55	< 1.0	7.0	< 0.3
10	10:03:20.33	68:44:01.82	3.8	1.4	< 17	0.34	< 0.8	4.3	< 0.4
11	10:03:20.24	68:44:04.33	3.7	2.2	< 17	0.55	< 2.0	6.9	< 0.7
12	10:03:20.24	68:44:03.83	2.5	1.9	< 17	0.60	< 1.5	7.6	< 0.5
13	10:03:19.96	68:44:02.34	2.5	2.1	< 17	0.62	< 1.8	7.8	< 0.5
14	10:03:20.15	68:44:03.83	-2.8	2.0	< 17	0.54	< 1.6	6.8	< 0.6
15	10:03:20.89	68:44:04.30	-4.0	1.8	< 17	0.51	< 1.4	6.4	< 0.5
16	10:03:14.10	68:44:09.05	-21.3	7.9	103	18.4	153	232	1.5

a) deconvolved

b) This assumes a 'standard' CO-to-H_2 conversion factor of $2.3 \times 10^{20}\,\rm cm^{-2}\,(K\,km\,s^{-1})^{-1}$, Strong et al. (1988) including a correction for helium. If the recalibrated conversion factor of $X = 1.6 \times 10^{20}\,\rm cm^{-2}\,(K\,km\,s^{-1})^{-1}$, Hunter et al. (1997) is used, all CO-based masses have to be reduced by $\sim 30\%$.

c) assuming $M_{H_2} = M_{vir}$

Note on errors: the measured quantities have the following errors: $\sigma(v_{lsr},dv)\sim0.6\ \rm km\,s^{-1}$, $\sigma(r)\sim 10\,\rm pc$, $\sigma(S_\nu) \approx 20\%$

($13.1'' \times 12.7''$) and the H_2 column density derived from employing a conversion factor (Sec. 3.2.2) was multiplied by two to get the proton density. The molecular gas has a clear inpact on the total gas column density map (reaching maximum surface densities of 5.2×10^{21} cm^{-2}). The total gas mass (atomic and molecular) in this plot is $\sim 9 \times 10^6\,M_\odot$.

The thick contours represent the orientation of the J–band image (2MASS) of NGC 3077[3]. The J–band image mostly shows the distribution of the old stellar population of NGC 3077 (see Sec. 3.3). It is evident that the apparent asymmetry of the gas discussed above is weaker if one considers the total gas column density. Nevertheless the gas distribution in the center of NGC 3077 is clearly displaced towards the south–east compared to the stellar distribution (tracing the potential of the galaxy). This implies that not only the gas in the outer parts of NGC 3077 has been affected by the tidal forces within the triplet but also the gas in the center. A similar displacement of the gaseous component with respect to the nucleus has been found in the center of M 82 (Weiß *et al.* 2001).

3.4. Distribution of Stars and Dust

The optical appearance of NGC 3077 is heavily influenced by dust absorption near the nucleus (see the study by Price & Gullixson 1989). In Fig. 8 we present a B–band image of NGC 3077. The contours again represent the J–band image of NGC 3077 as obtained from the 2MASS survey. A NICMOS H–band image obtained on board HST of the same region is presented on the right side of this figure. The near infrared image mainly shows the distribution of the older stellar population in NGC 3077.

Fig. 9 (left) shows the same broad band image as Fig. 8. The contours in the left panel

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[3]note that the registration of the 2.2μm image presented in Price & Gullixson (1989) is off by $\sim 10''$

of Fig. 9 are the OVRO CO contours as presented in Fig. 6. The dust feature in the south coincides very well with the regions R1 and R2 where we detected molecular gas. This finding implies that CO is a good tracer for dust in NGC 3077. Price & Gullixson (1989) derive an H I mass of $10^5\,\mathrm{M}_\odot$ for the absorbing cloud. Our CO–data implies a total virial mass of $< 5 \times 10^5\,\mathrm{M}_\odot$ (only summing up the complexes C1 to C11). The difference might indicate that not all clumps (1-11) are associated with the foreground dust extinction. This view is supported by the fact that this particular region shows a large CO velocity gradient, suggesting a large distance between individual clouds along the line of sight (see Sec. 3.5).

The optical images of NGC 3077 also reveal the presence of radial absorption features (indications can be already seen in Fig. 9, left). The dust lanes look similar to the spokes of a cartwheel; they are aligned radially in the north–west, however they look more 'curved' in the south–east (see the discussion in Sec. 4). Some of these dust lanes are associated with weak Hα emission as far out as 500 pc from the center. To reproduce this situation we present 5 intensity profile cuts parallel to the right ascension in B–band as well as in Hα emission. The intensity cuts are indicated as 5 lines in Fig. 11 and are plotted in Fig. 9 (right). The lines showing the absorption represent the B–band emission along one cut; the Hα intensity profiles show emission.

3.5. True location of the starburst: Hα and Paα observations

Major parts of the ongoing star formation in NGC 3077 as traced by Hα emission is hidden by the central dust cloud (Sec. 3.3). To reveal the true location of the starburst we analyzed Paα imaging (NICMOS, HST). The Paα image is presented in Fig. 10 (right) – our ground–based Hα image of the same region is shown on the left side of the figure. As discussed in Martin (1998) the central starburst region is surrounded by expanding Hα shells which are breaking out from the center (these shells are also visible in Paα).

The brightest Hα emission is located just north of the molecular complexes R1 and R2. Thronson *et al.* (THR891998) suggested that this morphology might be indicative for a confinement of the ionized gas to the south and east where the molecular complexes and the H I column density peak are located. However, from the Paα imaging it is obvious that major parts of the starburst are hidden by the dust feature discussed in Sec. 3.3. The contours in the right panel of this Fig. 10 again represent the CO emission from our high–resolution OVRO data (see Fig. 13 for a color composite).

The Paα emission peaks right in between the regions R1 and R2 where only a minor fraction of Hα is detected. This implies that due to absorption the Hα emission in NGC 3077 only partly traces the ongoing star formation. This view is supported by our observations in the radio continuum at 21 cm which are shown as contours in the left panel of Fig. 10. Although our resolution of $5''$ (~ 80 pc) is too poor to resolve the emission, the radio continuum emission clearly shows that the most active starforming region is associated with the molecular complexes R1 and R2. A comparison between the CO kinematics and our Hα slit spectroscopy (Fig. 12, the orientation of the slit is indicated in Fig. 10, left) in this particular region reveals another interesting aspect: the center velocity of the Hα emission is between the velocities of the molecular complexes R1 and R2. It is suggestive that this region of strong star formation has disrupted its parental molecular cloud which was located between R1 and R2 . Note that even the faint diffuse CO complex R4 in the north–west (Sec. 3.2.1) coincides with Hα emission at the same velocity.

A quantitative analysis of the narrow band images shown in Fig. 10 yields a total Paα flux of NGC 3077 of F(Paα)=$7.8 \times 10^{-13}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (consistent with the value derived by Böker *et al.* 1999). The total Hα flux is F(Hα)=4.4×10^{-12} $\mathrm{erg\,cm^{-2}\,s^{-1}}$ (L(Hα)=$5.33 \times 10^{39}\,\mathrm{erg\,s^{-1}}$, using $L = 4\,\pi\,D^2 F(H\alpha)$).

The Paα/Hα intensity ratio in the outer parts of NGC 3077 (where the absorption of

Hα is negligible) is about 0.17. This is close to the ratio of the emission coefficients for $T = 10^4\,$K and Case B recombination of $j(\mathrm{Pa}\alpha)/j(\mathrm{H}\alpha) = 0.12$ (Osterbrok 1989, Table 4.4). The highest absorption in the galaxy is found close to the Paα peak (intensity ratio (Paα/Hα) = 1.30). This corresponds to a local extinction for this particular region of about an order of magnitude ($\sim$2.5 mag).

If there was no extinction we would expect an Hα flux of $5.2\times10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ based on the observed Paα flux (L(Hα)=$6.30 \times 10^{39}\,\mathrm{erg\,s^{-1}}$). We used SFR($\mathrm{M_\odot\,yr^{-1}}$)=L(H$\alpha$)/($1.26 \times 10^{41}$) $\mathrm{erg\,s^{-1}}$ (Kennicutt *et al.* 1994) to derive a star formation rate (SFR) based on the extinction corrected Hα emission of $0.05\,\mathrm{M_\odot\,yr^{-1}}$. This is some 25% larger than the value obtained from the Hα emission alone and is a measure for the total extinction within NGC 3077. Note that this is a factor of a few less than the value derived by Meier, Turner & Beck (2001) who used 2.6 mm radio continuum emission to derive the SFR in NGC 3077.

3.6. Outflow of Ionized Gas vs. H I morphology

The outflow in NGC 3077 (as traced by Hα and Paα emission) reaches galactocentric distances of up to 1.5 kpc. Given the intrinsic small size of NGC 3077 this is remarkable (for a detailed discussion see Martin 1997). At larger scale, an anti–correlation between diffuse H I and the Hα outflow is evident: In Fig. 11 we plot the H I in blue and the Hα in red (for comparison, the optical broad band image is shown in green as well). At large galactocentric radii, the H I is predominantly situated *around* the expanding shells. Typical H I surface densities at these galactocentric radii are $4 - 9 \times 10^{20}\,\mathrm{cm^{-2}}$. One explanation for these feature may be that the pressure of the interior of the Hα shells is high enough to push the H I out to larger radii.

4. Discussion and Summary

The wealth of data presented here give exciting new insights on the interplay between the atomic gas, molecular gas and ongoing star formation in NGC 3077. The total (atomic and molecular) gas content in the centre of NGC 3077 is clearly displaced from the stellar component of NGC 3077 – this implies that not only the gas at large galactocentric radii is affected by the interaction within the triplet. The H I mass associated with NGC 3077 is $3-10\times10^{7}\mathrm{M}_{\odot}$(depending on the aperture chosen, Sec. 3.1). It was suggested in numerical studies of the triplet that the tidal material around NGC 3077 originally belonged to NGC 3077 itself; the high–resolution data of the H I morphology and kinematics show observational evidence for this scenario.

Based on the OVRO interferometer data we estimate a molecular mass of 1.6×10^{6} $\mathrm{M}_{\odot}$for NGC 3077 (Sec. 3.1.2). In total, 16 complexes have been detected with our $2''$ ($\sim 30\,\mathrm{pc}$) beam. All of the complexes have virial masses which are lower than the masses calculated from the CO luminosity (assuming a Galactic conversion factor). This implies that the conversion factor for NGC 3077 is lower than the Galactic value. At first glance, this seems surprising since the conversion factor is usually believed to be higher in dwarf galaxies as compared to spirals such as our own Galaxy (Arimoto *et al.* 1996, Wilson 1995). However, the metallicity of NGC 3077 is high (O/H around solar) for a dwarf (Martin 1998), so this objection may not apply. The higher CO emissivity and lower conversion factor can also be understood by an increased kinetic temperature and cosmic–ray heating near the starburst powering the outflow in NGC 3077. E.g., in the case of M 82, Weiß et al. (2001) have shown that X_{CO} may be as low as $3\times10^{19}\,\mathrm{cm}^{-2}\,(\mathrm{K\,km\,s}^{-1})^{-1}$. The prominent star forming regions as well as the outflow visible in Hα and Paα, as well as the radio continuum source near the starburst already suggest that the state of the molecular gas in NGC 3077 may be affected by the starburst (similar to the case in M 82). Indeed, as already

pointed out by Becker *et al.* (1989), a CO(2-1)/CO(1-0) line intensity ratio of 0.82 (on a T_A^* scale) indicates that a substantial fraction of the gas is heated to kinetic temperatures > 10 K. In a more recent study Meier *et al.* 2001, using observations in the CO(3-2) transition, estimated a kinetic gas temperature in NGC 3077 of $T_{kin} \approx 30$ K using LVG calculations. We note that the CO(2-1)/CO(1-0) line intensity ratio of 0.82 as reported by Becker *et al.* (1989) refers to antenna temperatures. Taking antenna efficiencies into account the CO(2-1)/CO(1-0) line intensity ratio is about 1.3 (T_{mb} scale, efficiencies as in Guelin *et al.* 1995) indicative for even larger temperatures. Using the ratio above and CO(3-2)/CO(1-0) = 0.7 (Meier *et al.* 2001; corrected for efficiencies at 115 GHz) we find $T_{kin} > 35$ K using LVG models. This supports the idea that the molecular gas in NGC 3077 is heated by the starburst resulting in a lower conversion factor (cf. Weiss et al. 2001 in the case of M 82).

We find a striking correspondence between the CO distribution and the dust cloud seen in the optical. From the Paα and Hα imaging we estimate the extinction in the central dust complex to be an order of magnitude (~ 2.5 mag). Surprisingly, CO emission is also coincident in position and velocity with a faint star forming region located 500 pc west of NGC 3077, far off the central star formation.

A comparison of the ionized outflow with the H I shows that the distribution of H I around NGC 3077's center is affected by the outflow. A puzzle is the presence of the 'radial' dust–fingers which reach lengths up to ~ 1 kpc. It may be that these dust lanes originally belonged to rudimentary spiral arms which have been ripped apart by the interaction. The dust lanes may have also been blown out of the NGC 3077's center by the violent SF (e.g., by radiation pressure). Somewhat counter–intuitively, the most prominent lanes are associated with Hα emission. One way to interpret the apparent correlation of dust with Hα is that the surface of the dust filaments is exposed to the strong radiation field of the

central starforming region which causes the weak Hα emission on the rim of the filament.

Correcting for extinction, we derive a star formation rate (SFR) of $0.05\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ for NGC 3077. Although this value does not look dramatic one has to keep in mind that the star formation in NGC 3077 is very concentrated towards the center. The effective area where massive star formation is found is $\sim 2 \times 10^4\,\mathrm{pc}^2$ resulting in a SFR per surface area of $2 \times 10^{-6}\mathrm{M}_\odot\,\mathrm{yr}^{-1}\mathrm{pc}^{-2}$, much higher than what is usually found in spiral galaxies (e.g. Martin & Kennicutt 2001).

We will now compare the neutral hydrogen, molecular gas and starburst properties of NGC 3077 to the corresponding parameters of the prototypical starburst galaxy M 82 (situated at a projected distance of only $\sim 70\,\mathrm{kpc}$). About 10% of the total gas mass (including the tidal arm) of NGC 3077 is associated with the optical galaxy; the corresponding fraction for M 82 is 70% (Yun et al. 1993b). This suggests that NGC 3077 lost most of its gas during the interaction whereas M 82 was able to hold it. The central starbursting region of M 82 still has a reservoir of about $2 \times 10^8\mathrm{M}_\odot$ of neutral hydrogen (more than $\sim$4 times the corresponding value of NGC 3077); the molecular gas content of M 82 is $2.2 \times 10^8\,\mathrm{M}_\odot$($\sim 140$ times higher than in NGC 3077, Weiß et al. 2001, $\mathrm{D}_{\mathrm{M82}}$=3.2 Mpc). The ratio of molecular to atomic gas in M 82's center is therefore of order unity, significantly higher than the same ratio in NGC 3077 (~ 0.05). This implies that the efficiency to form molecular out of atomic gas is much higher in M 82 as compared to NGC 3077. Interestingly the star formation efficiencies (SFE) are similar in NGC 3077 and M 82: our Hα and CO observations yield a SFE for NGC 3077 of $\mathrm{L}_{\mathrm{H}\alpha}/\mathrm{M}(\mathrm{H}_2) \approx 1\,\mathrm{L}_\odot\,\mathrm{M}_\odot{}^{-1}$ ($\mathrm{L}_\odot$=$3.82 \times 10^{33}\,\mathrm{erg\,s}^{-1}$. The corresponding value for M 82 is about $\approx 0.3\,\mathrm{L}_\odot\,\mathrm{M}_\odot{}^{-1}$ (adopting $\mathrm{L}_{\mathrm{H}\alpha} = 2.3 \times 10^{41}\,\mathrm{erg\,s}^{-1}$; Heckman *et al.* 1990, the true Hα flux in the centre of M 82 is presumably somewhat higher due to the edge–on orientation of M 82).

In that sense NGC 3077 can be regarded as a scaled–down version of M 82: it has a

similar star formation efficiency and shows a prominent outflow. The ‘only’ differences may be that the overall total masses are different and that NGC 3077 lost a larger fraction of its atomic gas during the interaction as M 82 did. In any case the starburst activity in both galaxies was presumably triggered by the redistribution of atomic and molecular gas in their centers due to the gravitational interaction within the M 81 triplet.

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Fig. 1.— *Left:* High–resolution VLA H I map of NGC 3077 and its environment. The contours represent the optical image (shown in greyscale on the right). The three ellipses define the apertures used for the H I mass determination. Note that most of the H I is not associated with the optical body of NGC 3077 but situated in a extended tidal arm towards the east. *Right:* Optical broadband image of the same region as shown on the left. The two boxes (labeled A, diameter: 2 kpc, and B, diameter: 1 kpc) are the regions which will be discussed in the next figures.

Fig. 2.— Velocity field of H I around NGC 3077. Velocities range from –60 $\mathrm{km\,s^{-1}}$(blue) to +40 $\mathrm{km\,s^{-1}}$(red). The box indicates the region shown in Fig. 1 (left). The black contours again represent the optical image. The 3 lines indicate the orientation of the position velocity diagrams shown in Fig. 3.

Fig. 3.— H I position velocity (pv) diagrams along 3 cuts through the tidal arms around NGC 3077 (see Fig. 2 for the orientation). The velocity resolution in these diagrams is 2.52 $\mathrm{km\,s^{-1}}$. The first pv diagram (I) cuts through the center of NGC 3077 and the prominent tidal feature. The bright emission at offset 2.3′ is NGC 3077 itself. Multiple velocity components are visible in the tidal feature (around offset -2′). The second (II) and third (III) pv diagrams are oriented along the prominent tidal arms which roughly point towards M 82 (north, cut II) and M 81 (west, cut III).

Fig. 4.— Channel maps of the natural weighted OVRO CO observations. Contour levels are 2, 4, 6, 8 $\times\sigma$ (1σ = 35 $\mathrm{mJy\,beam^{-1}}$, 0.29 K, beamsize: $3.7\times3.0''$, channel seperation: 1.3 $\mathrm{km\,s^{-1}}$).

Fig. 5.— Position–velocity diagram through the high–resolution OVRO CO cube (as indicated by a line in Fig. 6. Note that the emission is breaking up in many smaller subclumps. The clumps listed in Tab. 4 which are visible in this diagram are labeled by their number (column 1, Tab. 4).

Fig. 6.— Integrated CO–map of NGC 3077 (the area shown is indicated by box B in Fig. 1, right). *Left:* based on the NATURAL data (resolution $3.7'' \times 3.0''$, ~ 50 pc), the line indicates the orientation of the position velocity cut shown in Fig. 5 *Right:* based in the ROBUST data ($2.4'' \times 1.9''$, ~ 30 pc). R1–R4 label the four regions discussed in the text.

Fig. 7.— *Left:* Integrated HI–map of the center of NGC 3077. The thin contours represent the H I surface density at 1, 1.5 and 2×10^{21} cm^{-2}. The thick contours represent the integrated CO emission (area as indicated by B box in Fig. 1, right). *Right:* Total proton column density map (H I+CO, convolved to the beamsize of H I). Contours are plotted at 1,2,3,4 and 5×10^{21} cm^{-2}. The thick contours represent NGC 3077 in J–band (2MASS survey). Note that the apparent assymetry gas/galaxy is weaker if one considers the total proton density.

Fig. 8.— *Left:* B–band image of NGC 3077 – the contours represent a J–band image as obtained from the 2MASS catalog (same contours as Fig. 7, right). Note that the two maxima do not coincide which indicates dust absorption south of the nucleus. *Right:* H–band image as obtained with NICMOS on board HST (area shown in both panels is indicated by box B in Fig. 1).

Fig. 9.— *Left:* B–band image of NGC 3077. The area shown is indicated by box B in Fig. 1, right. The contours are the high–resolution CO data. The CO emission beautifully coinides with the aborption feature south of the nucleus. *Right:* 5 intensity cuts (B–band as well as Hα) along the lines shown in Fig. 11. The intensity (A.U.) is plotted versus position. Note that the B–band profiles show extinction where the Hα shows emission. For presentation purposes we subtracted the broad underlying Hα and B–band emission (by subtracting baselines).

Fig. 10.— *Left:* Hα image of NGC 3077 – the contours represent radio continuum emission at 21 cm (contours drawn at 2, 3, 4, 5 mJy beam^{-1}. The line indicates the position velocity cut shown in Fig. 12. *Right:* Paα image of NGC 3077 as obtained with NICMOS (HST). The contours represent the CO observations. Note that most of the starburst is hidden by the dust absorption feature (as traced by the CO – see Fig. 8, left). Both sides display the same region as indicated by box B in Fig. 1.

Fig. 11.— Color composite of NGC 3077: Blue: H I, Red: Hα, Green (B–band). The region plotted is indicated by box A in Fig. 1. The 5 yellow lines indicate the positions of the intensity cuts presented in Fig. 8 (right). Note how the Hα outflow seems to be confined by the huge H I halo (see also text).

Fig. 12.— Position velocity cuts along the line indicated in Fig. 9. The greyscale represents the Hα velocities – the contours are the CO velocities.

Fig. 13.— Color composite of NGC 3077: Blue: NICMOS H–band, Red: Hα, Green: CO (OVRO). The region shown is indicated by box B in Fig. 1.

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